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CORONAL X-RAY EMISSION FROM THE STELLAR COMPANIONS TO TRANSIENTLY ACCRETING BLACK HOLES

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ABSTRACT

Many neutron stars and black holes are in binaries where the mass transfer rate onto the compact object is highly variable. X-ray observations of these transients in quiescence ($L_x < 10^{34}$ erg s^{-1}) have found that the binaries harboring black holes are much fainter than those that contain a neutron star. Narayan and collaborators postulated that the faint X-ray emission from black hole binaries was powered by an advection dominated accretion flow (ADAF). The subsequent ADAF modeling requires that an appreciable fraction of the constant Roche-lobe overflow into the outer disk proceeds into the black hole during "quiescence". A robust and nearly uniform quenching mechanism must then be hypothesized for the neutron star binaries, as comparably large accretion rates would lead to luminosities in excess of 10^{36} erg s^{-1} in quiescence.

We explore an alternative explanation for the quiescent X-ray emission from the black hole systems: coronal emission from the rapidly rotating optical companion. This is commonly observed and well studied in other tidally locked binaries, such as the RS CVn, Algol and By Dra systems. We show that two of the three X-ray detected black hole binaries (A0620–00 and GRO J1655–40) exhibit X-ray fluxes entirely consistent with coronal emission. The X-ray spectra of these objects should be best fit with thermal Raymond-Smith models rich in lines when coronal emission predominates, a prediction that will be tested with *Chandra* and *XMM-Newton* observations. One black hole system (V404 Cyg) is too X-ray bright to be explained as coronal emission, and remains a candidate for ADAFs in quiescence. The quiescent X-ray emission from all the neutron star binaries is far too bright for coronal emission. It might be that all SXT's have variable accretion rates in quiescence and that the basal quiescent X-ray flux is set by either coronal emission from the companion or – when present – by thermal emission from the neutron star.

We have also searched for other indicators of coronal activity in these companion stars. For example, we show that the lithium abundances in the black hole systems are comparable to those in the RS CVns. Indeed, *both* the X-ray flux and lithium abundance from the K star in the binary V471 Tau match that of A0620–00. Though the production mechanisms for lithium in active coronae is still under debate, our work makes it clear that there is no longer a need for mechanisms that involve the compact object.

Subject headings: accretion, accretion disks — binaries: close — black hole physics — stars: individual (Aql X–1, Cen X–4, 4U 1608–522, 4U 2129+47, A0620–00, GS 1124–68, GRO J1655–40, V404 Cyg, GS 2000+25, GRO J0422+32, 4U 1543–47, H 1705–25) — X-rays: stars

1. INTRODUCTION

It is a mystery as to what powers the X-ray emission from transiently accreting neutron star and black hole binaries (collectively referred to as soft X-ray transients, SXTs) when they are in their faint, quiescent state ($L_x < 10^{34}$ erg s^{-1}). The cause of the bright outbursts is the sudden accretion of material that has accumulated in the outer disk, just as in the dwarf novae systems (see King 1999 for a recent discussion). While the majority of the SXT's containing neutron stars have been detected in quiescence, only three SXTs that contain black holes have been detected: A0620–00 (McClintock et al. 1995), V404 Cyg (Verbunt et al. 1994; Wagner et al. 1994), and GRO J1655–40 (Hameury et al. 1997). While there is agreement that neutron stars (NS) are, on-average, brighter in quiescence than the black-hole candidates (BHCs) (Barret et al. 1996; Narayan et al. 1997b; Asai et al. 1998), the sources of the quiescent emission are still under debate.

Several possible mechanisms for the NS quiescent emission have been introduced, including accretion (Van Paradijs et al. 1987; Menou et al. 1999) and magnetospheric emission from a turned-on radio pulsar (Campana et al. 1998b). Recent theoretical (Brown et al. 1998) and observational work (Rutledge et al. 1999; Rutledge et al. 2000) successfully attributes much of the quiescent luminosity of the transiently accreting NSs to thermal emission from the NS surface. The repeated deposition of nuclear energy deep in the crust (about 1 MeV per accreted baryon) during outbursts keeps the core of these accreting neutron stars hotter than their age would suggest (Brown et al. 1998). The luminosity of the thermal emission is then fixed by the time-averaged accretion rate – integrated over many outbursts – to be $\approx 6\times10^{32}$ erg s$^{-1}(\langle\dot{M}\rangle/10^{-11}M_\odot$ yr$^{-1})$.

The only emission mechanism available to the quiescent black hole is accretion. The puzzle of their emission mechanism began when ROSAT/PSPC detected X-rays from A0620–00 at a level $L_x \approx 6\times10^{30}$ erg s^{-1} (McClintock et al. 1995). McClintock et al. (1995) made it clear that this X-ray emission could not be due to a steady-state accretion disk around the black hole, as if so, there would be a production of optical and UV photons from the outer parts of the disk which

would far exceed that observed. This puzzle can be solved with an advection-dominated accretion flow (ADAF), making it a commonly discussed energy source for the BHC quiescent X-ray emission (Narayan et al. 1997b; Narayan et al. 1997a; Yi & Narayan 1997; Quataert & Narayan 1999). In this case, the X-rays are produced via Compton up-scattering of the optical/UV synchrotron emission from the flow close to the black hole. These models much more successfully handle the ratio of optical/UV emission to X-ray emission, which is critical in evaluating their success (§4.4). These models require large accretion rates in quiescence; fully a third of the mass transfer rate in the binary (see Meyer-Hofmeister & Meyer 1999 for a discussion).

In this paper, we investigate the alternative hypothesis that some or all of the quiescent X-ray emission from the BHCs originates from the active corona of the rapidly rotating and convective stellar companion. Coronal X-ray emission from the companion star has not been examined in any detail previously. McClintock et al. (1995) concluded that the X-ray luminosity of coronally active stars was too low to explain BH SXT emission ($L_x < 10^{30}$ erg s^{-1}), referring to a comparison between the X-ray luminosity of CVs and unevolved K dwarfs in the Pleiades made by Eracleous et al.(1991). However, the more analogous systems are tidally locked (and slightly evolved) stars in tight binaries, such as the RS CVn and Algol systems. These have X-ray luminosities from coronal activity that can reach 10^{32} erg s^{-1}(Dempsey et al. 1993b). The analogy between quiescent BHCs and the RS CVn binaries was further noted by Verbunt (1996), and we confirm his initial findings about the X-ray emission.

In § 2, we briefly discuss coronal X-ray production in other tidally locked binaries, making it clear what level of X-ray emission is possible from the SXT companion stars. We find that the X-ray emission from two (A0620–00 and GRO J1655–40) of the three detected BHCs is consistent with coronal emission, while one BHC (V404 Cyg) and all NS systems are too bright to be explained with coronal emission from the companion. The implications this has for future X-ray observations are discussed in §3. Possible radio and/or optical confirmation of the coronal hypothesis is discussed in §4. When first noting the prominent Li absorption line in the SXT V404 Cyg, Wallerstein (1992) considered the hypothesis that Li was overabundant as in an RS CVn binary. Though he discarded it because he estimated the Li to be too abundant, we feel this was premature. Our investigations into coronal indicators find that the lithium detected in many of the SXT companions is likely from coronal activity, thus eliminating the need for exotic mechanism having to do with the compact object. We conclude in § 5 and mention a few tests for coronal X-ray emission in these systems. We also outline the implications our work has for the general picture of accretion in quiescence in the SXTs.

2. STELLAR CORONAL X-RAY ACTIVITY AND COMPARISONS TO SXTS

The level of coronal activity for stars with outer convective zones strongly depends on the stellar rotation rate (see Noyes et al. 1984). The simplest dynamo picture requires rotation and a radiative layer underneath the convective zone. This naturally occurs in late-type main sequence stars (spectral types F through M) where the accumulated X-ray observations point to the ratio of soft X-ray to bolometric luminosities ($L_x/L_{\rm bol}$) saturating at a level of $\approx 10^{-3}$ (Vilhu & Walter 1987) toward short rotation periods ($\lesssim$1 day) (Singh et al. 1999). This saturation level decreases for rotation periods longer than a few days and appears to be independent of stellar age (Singh et al. 1999).

The inevitable slowing of isolated stars with age means that high levels of activity can best be maintained for long times via tidal locking in a tight binary. The common systems that result are the RS CVn, Algol and By Dra type binaries; many of which are prevalent X-ray sources in old open clusters, such as M67 (Belloni et al. 1998). The X-ray properties of RS CVns were surveyed by Dempsey et al. (1993b), who found 112 such objects in the *ROSAT* All-Sky Survey. They found that most rapidly rotating (less than ten days) late type dwarfs exhibit $L_x/L_{\rm bol} \approx 10^{-4} - 10^{-3}$, with some systems exceeding the 10^{-3} level that Vilhu and Walter (1987) had denoted previously as a possible "saturation" limit. Dempsey et al. (1997) found much the same X-ray properties for the BY Draconis dwarf-type binaries.

The companion stars in the SXTs are also rapidly rotating through tidal locking and have rotation rates and spectral types similar to these active systems (Verbunt 1996). This amplifies the need to carefully assess the likelihood that a significant part of the observed soft X-ray emission in these binaries is from coronal activity. We start by making the simplest comparison between the SXT companions and the active binaries, which is the ratio of the X-ray to bolometric flux, $L_x/L_{\rm bol}$. This *distant-independent* quantity immediately tells us which SXTs could possibly have substantial X-ray emission from active coronae.

2.1. *Measuring $L_x/L_{\rm bol}$ for the SXTs*

The SXTs we analyze are the optically identified, spectroscopically typed SXTs with low quiescent luminosities ($\lesssim 10^{33}$ erg s^{-1}; Chen et al. 1997; Menou et al. 1999). This gives us eight BHCs: GRO J0422+32, A0620–00, GS 1124–68, GRO J1655–40, 4U 1543–47, H 1705–25, GS 2000+25 and V404 Cyg; and four NSs: Aql X–1, Cen X–4, 4U 1608–522, and 4U 2129+47.

Here, we give the details of measuring $L_x/L_{\rm bol}$ for the SXTs. To obtain X-ray fluxes in the *ROSAT*/PSPC passband (0.4-2.4 keV) for comparison with coronal sources, we re-fit X-ray data from our previous studies of these objects (Rutledge et al. 1999; Rutledge et al. 2000), and converted the upper-limit fluxes for those we had not previously analyzed (specifically, 4U 1543–47 and H 1705–25) using W3PIMMS[1]. For the fits, we assume all the X-ray emission is from the stellar corona, and use a Raymond-Smith plasma plus galactic absorption column, as implemented in XSPEC v10.0 (Arnaud 1996), with solar-abundance, and holding the column density $N_{\rm H,22}$(=$N_{\rm H}$/[10^{22} cm^{-2}]) fixed at the values we previously adopted for each source, except where noted. To obtain 2σ upper-limits, we assume kT_{RS}=1.0 keV.

The BHC data we analyse here are of low signal to noise. For example, A0620–00 has only 45 +/- 9 counts. Binned into 3 PHA spectral bins, these data can be adequately fit with nearly any model (power-law, blackbody, bremmstrahlung). It is our present goal to only interpret the X-ray flux as from a stellar corona, which motivates our selection and application of a Raymond-Smith plasma model. The current data do not allow us to test the hypothesis based on the spectral fits. These data have been previously analysed in a wide range of models, and we refer the interested reader of the results of such analyses to

[1]http://heasarc.gfsc.nasa.gov

those studies (Rutledge et al. 2000, and references therein).

After measuring the unabsorbed X-ray flux $F_{\rm X,unabs.}$ (0.4-2.4 keV), we also find the bolometric luminosity of the stellar companion $F_{\rm bol} = 10^{-0.4(V_q+\delta V_{\rm exc}+11.51+B.C.-A_V)}$ erg cm^{-2} s^{-1}(Zombeck 1982, p. 102), where V_q is the quiescent magnitude, $\delta V_{\rm exc}$ is a correction due to the non-stellar continuum (see §4.4 for a discussion), B.C. is the bolometric correction for the measured spectral type, and A_V is the reddening.

To estimate $\delta V_{\rm exc}$ we examined all previous measurements of the fraction (f) of the optical continuum that is not from the stellar companion (see Table 2). These measurements were taken in different passbands, from different objects, often using different techniques and at different times, some with and others without error estimation. The vast majority are $f \lesssim 50\%$. Four measurements of the $\sim$30 we list are above this and we therefore consider a $> 50\%$ flux contribution to be exceptional (the data of Harlaftis et al. 1996 is the same as Filippenko et al. 1997). Note especially the values by Orosz et al.(1996) for GS 1124–68 and (1997) for GRO J1655–40, which indicate a time-variable f. While it would be highly preferable to apply individual — and more precise — estimates of this contribution for the individual sources, such contributions must be measured simultaneously with the photometric measurement, due to the observed time-variability of f, and these are generally not available. We adopt $\delta V_{\rm exc} = 0.4 \pm 0.4m$, which includes a conservative uncertainty for this correction. Aside from uncertainty in disk contribution we estimate the uncertainty in $F_{\rm bol}$ to be dominated by uncertainty in the B.C. and A_v. Our (conservative) uncertainties in the B.C. are found from the effect of the uncertainty of the companion's spectral type on the assumed B.C. The uncertainties in V_q are small compared to these, so we neglect them.

We use the following conversions: $A_V = 3.1\ E(B-V)$, (Schild 1977); $N_{\rm H}$=0.179 $A_V 10^{22}$cm^{-2} (Predehl & Schmitt 1995). We now describe the details of the calculation as it differs from this description, as applied to each source, and the statistical quality of the best-fit. Table 1 shows the derived $F_{\rm X,unabs.}$ and $F_{\rm bol}$ values as well as the information used to derive them.

Aql X-1. As in our previous work (Rutledge et al. 1999), we used the two ROSAT/PSPC observations and the ASCA observation in a simultaneous fit, imposing an identical spectrum, but permitting the three values of the column density to vary independently (if we require all three column densities to be equal, the fit is statistically unacceptable, as previously). The spectral fit was only marginally acceptable (χ^2_ν=1.38/78 degrees of freedom=dof; prob=0.015), and kT_{RS}=1.38±0.05 keV.

Cen X-4. We let the column density vary. While the best-fit spectrum was statistically unacceptable (χ^2_ν=1.82 for 90 dof; prob=310^{-6}), we use this to estimate the $F_{\rm X,unabs.}$(we estimate the flux uncertainty at 10%, although the spectral uncertainty is greater).

4U 1608–522. We alternately adopted the two values of $N_{\rm H,22}$=0.8 and 1.5 (cf. Rutledge et al. 1999; Wachter 1997). We thus find kT_{RS}=1.2±0.1 keV (0.6±0.04 keV) and $F_{\rm X,unabs.}$=1.6×10^{-12} (1.3×10^{-11}) erg cm^{-2} s^{-1}for χ^2_ν=1.52 (1.34; 61 dof) with probabilities prob=0.004 (prob=0.03) for the two listed $N_{\rm H}$ values, respectively. The uncertainties in the flux values were $^{+40\%}_{-20\%}$. No orbital period and only loose constraints on the spectral type of the companion QX Nor in quiescence (luminosity class IV-V, spectral class G0-K0, assuming $d \gtrsim 3.0$ kpc) have been obtained for this source (Wachter 1997). We adopt the quiescent J = 18 of Wachter (1997), $(V-J)_0$ =1.05–1.43 (Zombeck 1982, p. 68), and the values $A_J = 1.6-2.5$ (for low and high values of $N_{\rm H}$). From this we obtain V_q=19.25±0.2

4U 2129+47. We re-fit our previous PSPC spectrum with $N_{\rm H,22}$=0.22 (Deutsch et al. 1996), obtaining kT_{RS}=0.82±0.06 keV(χ^2_ν=0.3/1 dof; prob=0.6). For the HRI data, we held $N_{\rm H,22}$=0.22 and kT_{RS}=0.82 keV fixed. We obtained $F_{\rm X,unabs.}$=1.2×10^{-13} and 2.1×10^{-13} erg cm^{-2} s^{-1} for the PSPC and HRI observations, respectively.

A0620–00. We obtained a best fit spectrum with kT_{RS}=0.6±0.4 keV, with an acceptable fit of χ^2_ν=2.8/1 dof (prob=9%).

4U 1543–47. We converted the X-ray flux 5σ upper-limit (Orosz et al. 1998), using our adopted $N_{\rm H}$=0.5 and kT_{RS}=1.0 keV, to estimate a 2σ upper-limit.

GRO J1655-40. The fit to *ASCA* data was acceptable (χ^2_ν=1.2/16 dof; prob=0.26). With both the temperature and normalization allowed to vary, the data provides only a lower limit for temperature of $kT_{RS} \geq$ 4.1 keV(90%), with an upper-limit in excess of 64 keV. At the best-fit, the uncertainty in flux (holding the temperature fixed) is 10%; across the range of temperatures 4.1-64 keV, the best fit flux ranges 30%. The flux measurement uncertainty then is dominated by uncertainty in the spectrum. We quote the best fit X-ray flux (6±1.2)×10^{-14} erg cm^{-2} s^{-1}, adopting a 20% uncertainty.

H 1705–25. We used the 4σ HRI countrate upper-limit (0.006 c/s; Verbunt et al. 1994), $N_{\rm H,22}$=0.27, and kT_{RS}=1.0 keV to estimate a 2σ upper limit.

GS 2000+25. We estimate the $V_{\rm q}$ from R=20.8 (Chevalier & Ilovaisky 1990), and $(V-R)_0$=0.99 of a K5V star (Zombeck 1982).

V404 Cyg. These data are such that we only find a lower limit of kT_{RS}>1.5 keV(90% confidence), where the flux is 78×10^{-14} erg cm^{-2} s^{-1}. At kT_{RS}=64 keV, the flux is 96×10^{-14} erg cm^{-2} s^{-1}. The uncertainty in flux (holding temperature fixed) is 5%; the X-ray flux uncertainty is then dominated by spectral uncertainty, where it is 20%. We adopt a flux value of (85±20)×10^{-14} erg cm^{-2} s^{-1}.

The consistency of these spectral fits with a Raymond-Smith plasma is not, in itself, supporting evidence for a coronal origin of the observed X-ray flux, as the data S/N are such that nearly any spectrum (black-body, power-law) would be consistent with them (see (Rutledge et al. 2000) and references therein). Rather, we applied Raymond-Smith spectra only to extract X-ray fluxes from the data, to produce the ratio L_x/L_{bol}, assuming that the X-rays are coronal in origin. We cannot rule out, on the basis of these X-ray spectra, that some other emission mechanism is responsible for the X-ray flux.

2.2. *Comparison of $L_x/L_{\rm bol}$ between SXTs and Active Binaries*

The measured ratios ($L_x/L_{\rm bol}$) are displayed in Figure 1 for the SXTs, as well as the RS CVNs (Dempsey et al. 1993b), as a function of the binary orbital period. We also include the best-fit line relating $L_x/L_{\rm bol}$ and rotation period for isolated late-type dwarfs (Singh et al. 1999). The $L_x/L_{\rm bol}$ ratios for the SXTs are uncertain by up to a factor of two, depending on the source. Two of the three X-ray detected BHCs (A0620–00 and GRO J1655–40, the exception being V404 Cyg) have $L_x/L_{\rm bol}$ ratios common to the RS CVns ($\lesssim 10^{-3}$). The four detected NSs are 10-1000 times above this value, clearly inconsistent with coronal X-ray emission. Five other BHCs (GRO J0422+32, 4U 1543–47, H 1705–25, A0620–00, GS 2000+25) have up-

per limits (some high, others less so) which are also consistent with RS CVn-like X-ray emission. *We conclude that the quiescent X-ray emission of some BHCs can be dominated by the coronal X-ray emission of the companion. This is not the case for the quiescent emission of NSs.*

Among the BHCs, V404 Cyg is clearly an outlier in $L_x/L_{\rm bol}$. The quiescent source is also spectrally harder than other BHCs and NSs (Rutledge et al. 2000). It is unclear if this can be associated with its highly variable outburst X-ray intensity profile, radio intensity profile and polarization, absorption column, and Fe line – all dramatically different from those observed from other transient BHCs (Kitamoto 1989; Han & Hjellming 1992; Oosterbroek et al. 1996).

The dwarf novae (DN) are another class of transiently accreting binaries, where white dwarfs undergo large accretion events after long periods of quiescence. They were found by *Einstein* to be X-ray sources (10^{30}–10^{32} erg s^{-1}) in quiescence (Cordova & Mason 1984; Patterson & Raymond 1985); raising much the same issues as we have discussed for the SXTs. However, in this case, Eracleous et al. (1991) clearly showed that the X-ray luminosities of the late-type rapidly rotating main sequence stars (that are the companions to these white dwarfs; Smith & Dhillon 1998) are too low ($\lesssim 10^{30}$ erg s^{-1}; Cruddace & Dupree 1984; Fleming et al. 1989) to explain the quiescent X-ray luminosities. Moreover, these CVs have $L_x/L_{\rm bol}\sim 10^{-2}$–10 (Richman 1996), well above the 10^{-3} saturation upper-limit observed in chromospherically active systems. This indicates that the majority of the measured X-ray emission is from accretion in quiescence. The typical quiescent accretion rate is a few percent of that transferred in the binary, and the X-rays should originate from the boundary layer near the white dwarf (Patterson & Raymond 1985). This has been confirmed via X-ray eclipse observations with ROSAT of three short orbital period DN in quiescence. These are HT Cas at P_o = 1.768h (Mukai et al. 1997), Z Cha at P_o = 1.788h (van Teeseling 1997) and OY Car at P_o = 1.515h (Pratt et al. 1999). All of these showed that the measureable X-ray emission was completely eclipsed when the white dwarf was behind the companion. No similar observations have yet been done for wider orbital period systems analogous to A0620–00.

3. IMPLICATIONS FOR FUTURE X-RAY OBSERVATIONS OF THE BHCS

We have shown that the quiescent X-ray emission from all but one BHC might be due to coronal emission from the companion star. Figure 2 shows the quiescent X-ray flux versus the bolometric flux of the companion star for the BHCs. The horizontal line displays the flux that can be reached in a 50 ksec *Chandra* observation with ACIS-S (assuming 1 count=5×10^{-12} ergs cm^{-2}, with 10 counts required for detection). This highlights what progress can be made. If most of the X-ray emission from the quiescent BHCs is of a coronal origin, it is unlikely that GRO J0422+32, H 1705–25 or GS 1124-68 will be detected. However, GS 2000+25 stands out as a potential *Chandra* detection. The stellar companion in GS 2000+25 is a K3-K6 dwarf tidally locked in a 0.344 day orbit (Chevalier & Ilovaisky 1993; Filippenko et al. 1995a; Harlaftis et al. 1997), much like A0620-00, and we expect coronal emission about at the *Chandra* detection limit.

Unlike all of the other BHC companion stars (which are later than mid F type, see Table 1), the stellar companion in 4U 1543-47 is an early type star of spectral type A2 V (Orosz et al. 1998). Hence, though it appears to be a detectable source with *Chandra*, we don't expect it to be detected as a coronal source. Our earlier discussion of coronal activity was independent of spectral type for mid to late-type stars. The story is different for A stars, where soft X-ray emission is at least two orders of magnitude weaker than in comparably rapid rotating late type stars (Simon et al. 1995). The likely reason is the declining strength (or even absence) of an outer convective zone in stars this hot. The brightest X-ray emission detected from an early A star is the rapid rotator HR 5037 (which has the same spectral type and rotation rate of the companion to 4U 1543-47) at $L_x/L_{\rm bol}\approx 1.5\times10^{-5}$ (Simon et al. 1995). Most other early A stars have upper limits at levels a factor of ten lower. Hence, we expect that no coronal emission will be detected from this companion, making it a "clean" system for studying alternate energy sources for quiescent X-ray emission, such as the ADAFs.

We also examined the prospects for detecting (with a 50 ksec *Chandra* observation) coronal X-rays from all BHCs listed in Chen et al.(1997), or discovered since that compilation. We require a spectral type, quiescent V magnitude and A_V in order to estimate the bolometric flux. Other than those we discuss elsewhere in this paper (for which there are stringent quiescent X-ray flux limits or measurements, see Fig. 2), only N Vel 1993 (=1009–45) has such values reliably measured (R=21.2$\pm$0.2, K7-M0V, Filippenko et al. 1999; and $E(B-V)$=0.2$\pm$0.05, (della Valle et al. 1997)). For $(V-R)_0$ = 1.15, B.C.=–0.9 (Zombeck 1982), A_R=2.3$E(B-V)$ (Fitzpatrick 1999), and assuming $L_x/L_{\rm bol}$=10^{-3}, we find the X-ray flux due to the corona should be 10^{-16} erg cm^{-2} s^{-1}, well below the *Chandra* 50 ksec detection limit.

With regards to XTE J1550-564, Jain et al. (1999) find a $B\approx 22$ source at the position of the X-ray object in quiescence, speculating it to be a type G V object, with A_V = 5.0 (an upper-limit based on radio measurements). For a G5V source, $(B-V)_0$ = 0.66 (Zombeck 1982), and B.C.= –0.1, producing $F_{\rm bol}\sim 8\times10^{-12}$ erg cm^{-2} s^{-1}. For $L_x/L_{\rm bol}\sim10^{-3}$, this implies $F_{\rm X,unabs.}\sim 8\times10^{-15}$ erg cm^{-2} s^{-1}. Alternatively, for a K0V star, with B.C.= –0.19 and $(B-V)_0$ = 0.82, $F_{\rm X,unabs.}$=10×10^{-15}. These unabsorbed fluxes (with $N_{\rm H,22}$=0.9) can be detected with *Chandra* or *XMM*. However, Sobczak et al. (1999) found through X-ray spectroscopy a value of $N_{\rm H,22}$=1.7-2.2, which for interstellar absorption ($N_{\rm H,22}$=0.179 A_V) implies $A_V\sim$ 9.5-12.2. This implies quiescent bolometric and coronal X-ray luminosities a factor of 100 higher than these estimates. Thus, the uncertainty in the expected coronal X-ray luminosity is dominated by the uncertain A_V.

4. INDICATIONS OF CORONAL ACTIVITY AT OTHER WAVELENGTHS

Though our work was motivated by the X-ray measurements, there are numerous other repercussions if the SXT companions are coronally active. Out of all the things we discuss here, perhaps the most important is our realization that the lithium seen in these systems is possibly from coronal activity.

4.1. *Lithium Absorption Lines in the SXT Companions*

The λ6708 Li line is an absorption line that originates in the stellar atmosphere of the companion. It has has been found to be anomalously strong (when compared to field stars of the same spectral and luminosity class) in V404 Cyg (equivalent width EW=290$\pm$50 mÅ; Martin et al. 1992; Martin et al. 1994a), A0620–00 (160$\pm$30 mÅ; Marsh et al. 1994) Cen X–4 (480$\pm$65 mÅ; Martin et al. 1994a); GS 2000+25 (270$\pm$40 mÅ; Filippenko et al. 1995a; Harlaftis et al. 1996),

and GS 1124–68(420 ±60 mÅ; Martin et al. 1996). Upper-limits on Li in Aql X−1 (<300 mÅ, Garcia & Callanan 1999) and GRO J0422+32 ($\leq$ 480 mÅ, Martin et al. 1996) are consistent with other SXT Li measurements. Following these obsevations, a number of Li production mechanisms which require the presence of a compact object were suggested (Martin et al. 1994b; Yi & Narayan 1997; Guessoum & Kazanas 1999); these have little *a priori* ability to predict the level of lithium abundance.

Lithium is also observed in RS CVns and other active stars with abundances above that from field stars (Pallavicini et al. 1992; Randich et al. 1993; Fernandez-Figueroa et al. 1993; Randich et al. 1994). The origin of the Li overabundance in the active systems remains unclear; however, there is a claimed statistical correlation — with a broad dispersion – between Li abundance and Mg II, which is used as a coronal activity indicator (Zboril et al. 1997; Zboril & Byrne 1998). If the SXT companions are chromospherically active, then their Li overabundance may be due in part to the same mechanisms – whatever these may be – which produce them in chromospherically active stellar systems. In Fig. 3, we show the distribution of detected Li abundances in chromospherically active systems (Pallavicini et al. 1992) and five SXTs (Martin et al. 1994a; Martin et al. 1996). Though slightly overabundant relative to the RS CVns, we see no need for production mechanisms special to the compact object.

It is also of interest to compare A 0620-00 with the pre-CV binary V 471 Tauri, which contains a white dwarf and a K2V star in a 12.5 hour orbit. Wheatley (1998) recently showed that the hard X-ray emission from this system is not eclipsed by the K star, demonstrating clearly that the emission is coronal from the K star at a level of $L_x/L_{\rm bol} \approx 10^{-3}$. Martin et al. (1997) had earlier found the lithium absorption line present with an equivalent width of 299 mÅ, and derived an abundance $N(\rm Li) \approx 2.3$. These parameters are all very similar to the K star companion to A 0620-00. The simplest hypothesis for both the X-rays and lithium is coronal activity.

4.2. *Radio Emission from Stellar-Coronal Sources*

Radio emission (4.9-8.5 GHz) has been compared with the soft X-ray flux measured with (*Einstein* and *ROSAT*) from stellar coronae of dM(e), dK(e), By Dra-type, RS CVns, and Algols (Benz & Guedel 1994) in which it was found that the X-ray and radio luminosities are correlated over a range of 10^8 in X-ray luminosity (as high as 10^{32} erg s^{-1}) and a range of 10^{10} of radio luminosity, represented by (Guedel & Benz 1993; Benz & Guedel 1994):

$$F_{\rm Radio} = 0.32 \left(\frac{F_x}{10^{-14}\ {\rm erg\ cm^{-2}\ s^{-1}}} \right) \frac{10^{\pm 0.5}}{\kappa}\ \mu{\rm Jy}, \qquad (1)$$

where κ is $\sim 0.17-1.0$ (κ=1.0 for dMe, dK, BY Dra and RS CVNs with two sub-giants, and κ =0.17 for the higher X-ray luminosity, $\gtrsim 10^{30}$ erg s^{-1}classical RS CVNs, Algols, FK Com and post T-Tauri stars).

For the quiescent X-ray fluxes of the detected BHCs in Table 1 (between 1.2–95$\times10^{-14}$ erg cm^{-2} s^{-1}) the corresponding radio fluxes are between 0.4–30 μJy, which are below reported upper limits for these sources: (<300 μJy at 4.8 GHz for A0620–00, <300 μJy at 4.8 GHz for GRO J0422+32, Geldzahler 1987; <500 μJy at 4.8 GHz for GRO J1655-40, Hjellming & Rupen 1996). This expected coronal flux density level is at or below the detection limits of present instrumentation, representing an observational challenge. On the other hand the factor of 10 dispersion in the X-ray/radio flux ratio may provide a fortuitous detection. If V404 Cyg X-ray emission were coronal, we would expect it to be detected with $F_{\rm radio} \sim 30-200\mu$Jy while at the reported X-ray flux.

4.3. *Optical and Ultraviolet Emission Lines*

There are a few studied optical and UV emission lines which are found in spectra of coronally active systems, including Mg II, Hα, and C IV. Here, we compare observations of these lines in SXTs to the same in the coronally active systems.

The Mg II H and K emission lines are indicative of chromospheric activity in the RS CVn binaries (Rucinski 1985; Fernandez-Figueroa et al. 1986) and have been detected in A0620-00 (McClintock et al. 1995; McClintock & Remillard 2000), Cen X-4 (McClintock & Remillard 2000) and GRO J0422+32 (Hynes & Haswell 1999). In A0620-00, the line shape was broad and single peaked, suggestive of a stellar origin from the star, rather than from a disk (where the lines are double peaked). The observed fluxes are $F(\rm MgII) > 10^{-3} F_{\rm Bol}$ in Cen X-4 and A0620-00 and $F(\rm MgII) \approx 10^{-2} F_{\rm Bol}$ in GRO J0422+32. These flux ratios are more than a factor of ten higher than is observed in even the most active binaries, where at maximum rotation rates, $F(\rm MgII)/F_{\rm Bol} \approx 2\times10^{-4}$ (see Rucinski 1985; Fernandez-Figueroa et al. 1986). Even when the X-ray flux ratio is approaching 10^{-3} in the active binaries (as we see in some of the BHC's), the flux ratio in the Mg II lines are still $< 3\times10^{-4}$. As an example, Dempsey et al. (1996) found Mg II fluxes about a factor of ten below that of the X-rays from the KI IV companion in the active binary V711 Tauri. The only possible way to explain the Mg II line emission from the BHC's as coronal is to attribute it to higher abundances of this α element, as recently reported by Israelian et al. (1999) in GRO J1655-40. It seems more likely that the Mg II emission originates in the accretion disk.

Another suggestive indication of coronal activity exists for Nova Oph 1977 (H 1705-25). Harlaftis et al. (1997) reported on their Doppler mapping of the Hα line emission, which allows for a secure identification of this emission with the outer accretion disk and the "splash point". In addition, they also reported evidence for Hα emission from the companion star itself. This might be indicative of coronal activity. However, they did not report the flux for this component and so we cannot compare it to the typical levels seen in other interacting binaries ($L_{\rm H_\alpha}/L_{\rm bol} \sim 3-16\times10^{-5}$; Barden 1985; Montes et al. 1995). From our estimate of $F_{\rm bol}$, and assuming rotational broadening of 50 km s^{-1}, this works out to 0.6-3$\times10^{-17}$ erg cm^{-2} s^{-1}Å^{-1}. This is comparable to the flux observed in a variable single-peaked Hα emission line, super-imposed on a double-peaked line – present in July, 1994, but absent in May, 1993 (Remillard et al. 1996a). However, variability in RS CVn Hα emission at this level has not been reported.

Finally, we note that C IV has been observed in the UV spectra of RS CVn sources, correlated with X-ray emission (Dempsey et al. 1993b). There are no reported C IV lines of SXTs in the literature, although it would seem that they should be present.

4.4. *Excess Optical/UV Light and ADAFs*

Nearly all optical observations in quiescence find evidence for excess optical/UV light over and above that from the companion (see McClintock & Remillard 2000 for a recent example, and Table 2). The most commonly invoked source of this

emission is an outer disk that is truncated at some finite inner radius in order to avoid over producing UV and X-ray emission. However, the advent of the ADAF models for the quiescent X-ray emission has modified this story, as the synchrotron emission from the inner parts of the ADAF flow can possibly explain the observed optical excess (Narayan et al. 1997a). In these models, the X-rays are made via Comptonization of the synchrotron photons from deeper in the flow. Indeed, an advantage of the ADAF models (which can't *a priori* predict the X-ray flux) is their ability to predict the ratio of the optical to the X-ray emission in a nearly model independent way. We begin by summarizing the state of modeling for V404 Cyg, as coronal emission appears unlikely to explain its quiescent X-ray emission.

The current best set of ADAF models (Narayan et al. 1997a; Quataert & Narayan 1999) simultaneously fit the quiescent excess optical and X-ray emission from V404 Cyg. The required mass transfer rate in the quiescent ADAF flow is comparable to the total mass transfer rate in the binary, implying the incoming material from the companion is shared between the hot advective flow and accumulation in the outer disk. All of the excess optical/UV emission is explained as synchrotron emission from the ADAF, and is emitted within a few tens of Schwarzschild radii of the $\approx 10 M_\odot$ black hole. The outer cool disk makes no contribution to the total excess emission in this model.

How do the ADAF models fare when a substantial part of the X-ray emission comes from the corona of the companion? The optical/UV excess from A 0620-00 is well measured, and ADAF modeling that fit the X-ray data over-predicted the optical/UV emission by factors as large as four (Narayan et al. 1997a). This conflict is alleviated if some of the observed X-rays are from the stellar corona, as then the ADAF contribution can be reduced to explain the optical/UV excess. In that case, the stellar corona and ADAF X-ray emission are comparable.

An alternative picture would be to explain all the BHC X-ray emission as coronal and the optical/UV excess as from a truncated outer disk. This situation seems likely for GRO J1655-40, as the current ADAF models that fit the X-ray data under-predict the optical/UV excess (Hameury et al. 1997). This system might best be explained with all X-ray emission coming from the stellar corona. Indeed, the detailed modeling by Orosz & Bailyn (1997) of the excess optical emission exclusively in terms of an outer disk was successful and required no ADAF flow.

5. DISCUSSION AND CONCLUSIONS

We have shown that two (A0620–00 and GRO J1655–40) of the three X-ray detected black hole binaries exhibit X-ray fluxes entirely consistent with coronal emission from the companion star. The upper limits on the remaining BHCs are also consistent with production via chromospheric activity in the secondary. In addition, we found that the photospheric lithium content measured for many of the SXT companions is typical for coronally active stars. We therefore conclude that the quiescent X-ray emission from all but one BHC might be due to coronal emission from the companion star. There are many ways to confirm the chromospheric hypothesis. The most straightforward is X-ray spectroscopy of the BHCs in quiescence with *Chandra*and *XMM-Newton*. Resolving the soft (0.2-2.0 keV) X-ray emission into the coronal line emission common for chromospheric emission would be strong confirmation. However, the calculated equivalent widths make their detection quite difficult (Narayan & Raymond 1999).

Additional means of confirming the chromospheric hypothesis is analysis of the Ca II H&K absorption lines, the "refilling" of which is correlated with the X-ray chromospheric surface flux (Maggio et al. 1987); or from similar analysis of the Ca II infra-red triplet, as performed by Dempsey et al. (1993a). Radio emission (5-8 GHz) observed from coronally active stars is correlated with X-ray luminosity; consistency between the $F_X/F_{\rm radio}$ of BHCs and that observed from coronally active stars would support the interpretation of the X-rays as due to stellar coronal activity. Coronal variability from flares (which occur roughly 40% of the time in RS CVn systems; Osten & Brown 1999) requires that such observations be carried out simultaneously in the X-ray and radio frequencies.

Not all quiescent SXT X-ray emission can be explained as coronal activity in the companion. The quiescent X-ray flux from the BHC V404 Cyg is a factor of ten brighter than can be explained as coronal emission and all four NSs (Aql X–1, Cen X–4, 4U 1608–522, 4U 2129+47) have quiescent X-ray luminosities which are at least ten times greater than expected from chromospheric emission alone. As noted in the introduction, much of the quiescent X-ray emission from the NS systems is naturally explained as thermal emission from the NS (Brown et al. 1998; Rutledge et al. 1999; Rutledge et al. 2000).

However, accretion power is the only choice for the unambiguous black hole candidate V404 Cyg. The current ADAF modeling requires accretion rates in quiescence of order $\dot{M} \sim 10^{-9} - 10^{-10} M_\odot$ yr^{-1}, a large fraction of the mass transfer rate in the binary. Quiescent accretion rates *at least three orders of magnitude lower* may be needed to explain the observed variability in some of the quiescent NSs (a factor of 4.2 ± 0.5 in 8 days from Cen X–4; Campana et al. 1997 and in 4U 2129+47, by a factor of 3.4 ± 0.6 between Nov-Dec 1992 and March 1994; Garcia & Callanan 1999; Rutledge et al. 2000). There is no simple reason why these accretion rates should be so different, although some scenarios have been investigated (Menou et al. 1999).

Much of the current debate about the role of accretion as a power source in quiescence centers around understanding what fraction of the continuous flow into the outer disk (which makes itself apparent via excess continuum emission and broad, double-peaked $H\alpha$ lines) accumulates there (for the next outburst) versus proceeding all the way into the compact object. The ADAF modeling of the BHCs require that the incoming flow is about evenly split, whereas the much more severe limits on quiescent accretion for the NS systems says that 99.9% of the accreted matter does not find its way to the compact object.

The observational situation is clearly in a state of flux. The upcoming X-ray observations of the previously detected SXTs will sort out the emission sources via X-ray spectral information, rather than just total fluxes. It might be that all SXT's have variable accretion rates in quiescence and that the basal quiescent X-ray flux is set by either coronal emission from the companion or – when present – by thermal emission from the neutron star.

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TABLE 1
$L_x/L_{\rm bol}$ FOR THE SXTS

Object	Sp. Type	V_q (mag)	A_V (mag)	B.C. [1] (mag)	$F_{\rm X,unabs.}$ [b]	$P_{\rm orb}$ (d)	$\log(\frac{F_{\rm X,unabs.}}{F_{\rm bol}})$+3.0
			Black Hole Candidates				
GRO J0422+32	M2V [2,15]	22.8 [15]	1.3±0.2 [20]	−1.8±0.3	<270	0.211 [15]	<4.5
A0620–00	K4-K7V [3]	18.2 [16]	1.21±0.06 [34]	−0.3±0.2	2.4±1.4	0.323 [25]	0.8±0.3
GS 1124–68	K3-K4V [4]	20.4 [17]	0.60±0.16 [21]	−0.35±0.2	<1.7	0.433 [26]	<2.2
4U 1543–47	A2V [5]	16.55 [5]	1.55±0.16 [5]	−0.25±0.2	<16	1.12 [5]	<1.3
GRO J1655–40	F3-F6IV [6]	17.5 [35]	4.0±0.3 [6]	−0.04±0.3	6±1.2	2.621 [27]	−0.1±0.3
H 1705–25	K3V [7,31]	22 [7]	1.4±0.5 [22]	−0.33±0.3	<18	0.521 [7,31]	<3.7
GS 2000+25	K3-6V [33,8]	21.8 [18]	4.65(±0.3)[c] [23]	−0.35±0.3	<0.57	0.344 [32,33]	<0.7
V404 Cyg	K0IV [9]	18.42 [19]	4.0±0.4 [19]	−0.19±0.1	85±20	6.471 [28]	1.4±0.3
			Neutron Stars				
Aql X-1	K7V [10]	21.6 [10]	1.5±0.3 [10]	−0.65±0.3	88±5	0.789 [29]	3.5±0.2
Cen X-4	K7V [11,12,13]	18.5 [11,12]	0.3±0.15 [11]	−0.65±0.3	36±4	0.629 [12,13]	2.3±0.2
4U 1608–522	G0-K0 IV-V	(see text)	(see text)	−0.13±0.3	$160/1300^{+40\%}_{-20\%}$	–	2.8/3.7±0.3
4U 2129+47	F6IV [14]	17.9 [14]	1.2±0.16 [14]	−0.09±0.3	12±2/21±7	0.218 [30]	1.5/1.7±0.2

REFERENCES.— 1, Zombeck 1982; 2, Harlaftis et al. 1999; 3, Murdin et al. 1980; 4, Casares et al. 1997; 5, Orosz et al. 1998; 6, Orosz & Bailyn 1997; 7, Remillard et al. 1996a; 8, Harlaftis et al. 1996; 9, Wagner et al. 1992; 10, Chevalier et al. 1999; 11, Blair et al. 1984; 12, Chevalier et al. 1989; 13, McClintock & Remillard 1990; 14, Deutsch et al. 1996; 15, Filippenko et al. 1995b; 16, McClintock & Remillard 1986; 17, McClintock et al. 1992; 18, see Sec. 1; 19, Casares et al. 1993; 20, Shrader et al. 1992; 21, Gonzalez-Riestra et al. 1991; 22, Griffiths et al. 1978; 23, Chevalier & Ilovaisky 1990; 25, McClintock & Remillard 1986; 26, Remillard et al. 1992; 27, Bailyn et al. 1995a; 28, Casares & Charles 1994; 29, Chevalier & Ilovaisky 1998; 30, Thorstensen et al. 1979; 31, Filippenko et al. 1997; 32, Chevalier & Ilovaisky 1993; 33, Filippenko et al. 1995a; 34, Wu et al. 1976; Oke & Greenstein 1977; 35, Bailyn et al. 1995b

[b] $F_{X,unabs.}$ in 10^{-14} erg cm^{-2} s^{-1} (0.4-2.4 keV)

[c] Assumed value

TABLE 2
EXCESS CONTINUUM FLUX CONTRIBUTIONS (f) FROM LITERATURE

Ref.	Obj.	f^a(%)	Passband
Casares et al. 1993	V404 Cyg	<10	R band
Casares & Charles 1994	V404 Cyg	<13	6400-6600Å
Callanan et al. 1996a	GS 2000+25	<12	K'(19500-23500Å)
Harlaftis et al. 1996	GS 2000+25	6±5	5700-6800Å
Filippenko et al. 1997	N Oph 1977	70-90[c]	6300Å
Harlaftis et al. 1997	N Oph 1977	63-74[c]	6250Å
Remillard et al. 1996b	N Oph 1977	40±20	5500Å
Orosz et al. 1996	GS 1124-68	39[b]	$B+V$ band
	GS 1124-68	52[b]	$B+V$ band
Casares et al. 1997	GS 1124-68	12-15	R band
Oke & Greenstein 1977	A0620-00	43±6	V band
Marsh et al. 1994	A0620-00	17±4	4400-5200Å
		6±4	5800-6800Å
McClintock & Remillard 1986	A0620-00	40±10	5500Å
McClintock et al. 1995	A0620-00	56±8[b]	5150-5300Å
		43±4	5150-5300Å
		37±5	5150-5300Å
		29±12	5150-5300Å
		43±7	5150-5300Å
		27±5	6350-6500Å
Filippenko et al. 1995b	GRO J0422+32	30-60	6300Å
Callanan et al. 1996b	GRO J0422+32	<30	V band
Harlaftis et al. 1999	GRO J0422+32	39±4	5600-6900Å
Orosz et al. 1998	4U 1543-47	10±5	B band
		21±5	V band
		32±5	R band
		39±5	I band
Orosz & Bailyn 1997	GRO J1655–40	50[b]	V band
	GRO J1655–40	5[b]	V band
Filippenko et al. 1999	N Vel 1993	60-70	6300Å
Chevalier et al. 1989	Cen X-4	>80	3800Å
		40-50	B-band
		25-30	V-band
		20	6500Å
McClintock & Remillard 1990	Cen X-4	25-30	V-band

[a]Fractional continuum flux contribution in listed passband

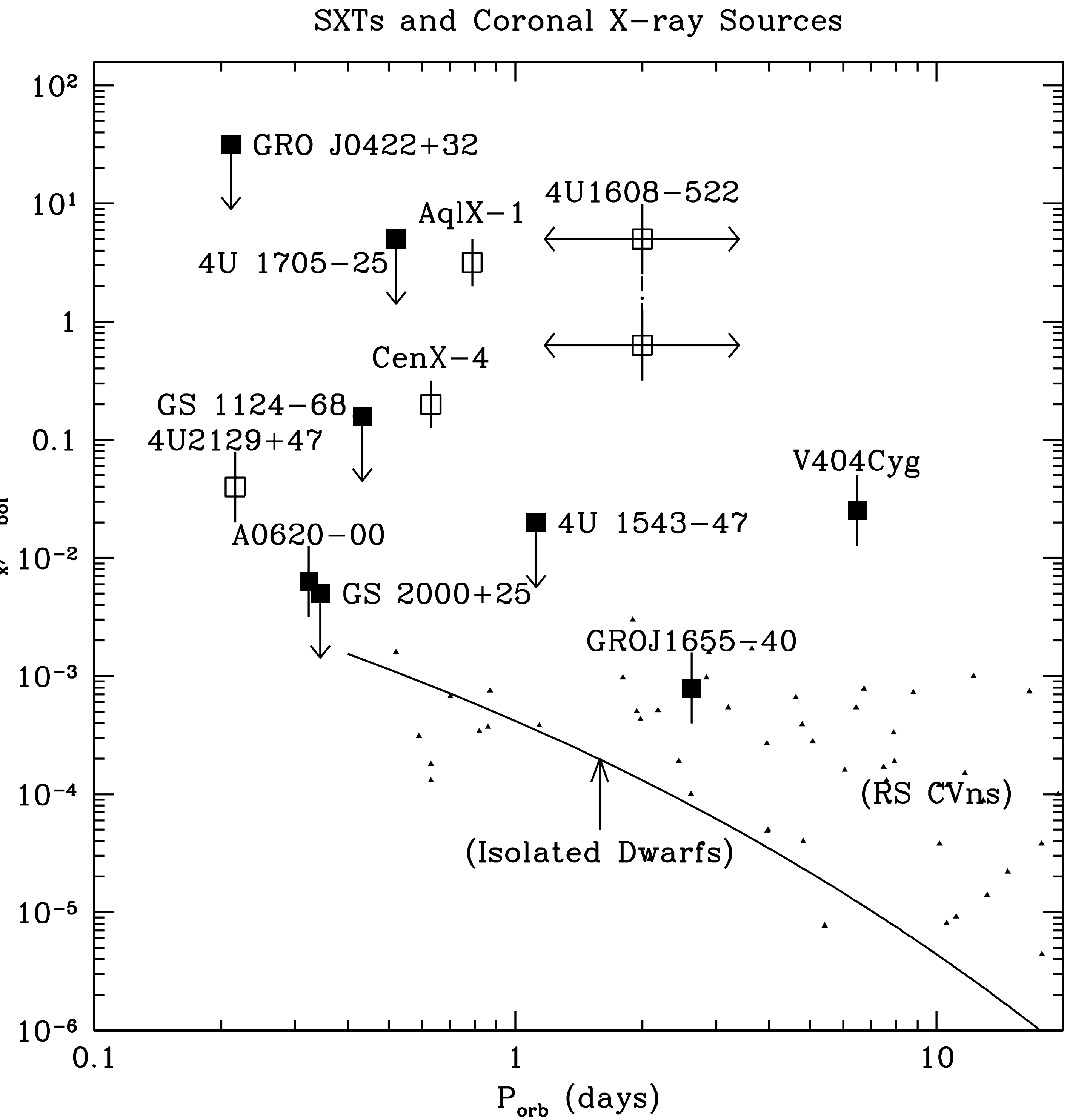
[b]Observations taken on different days

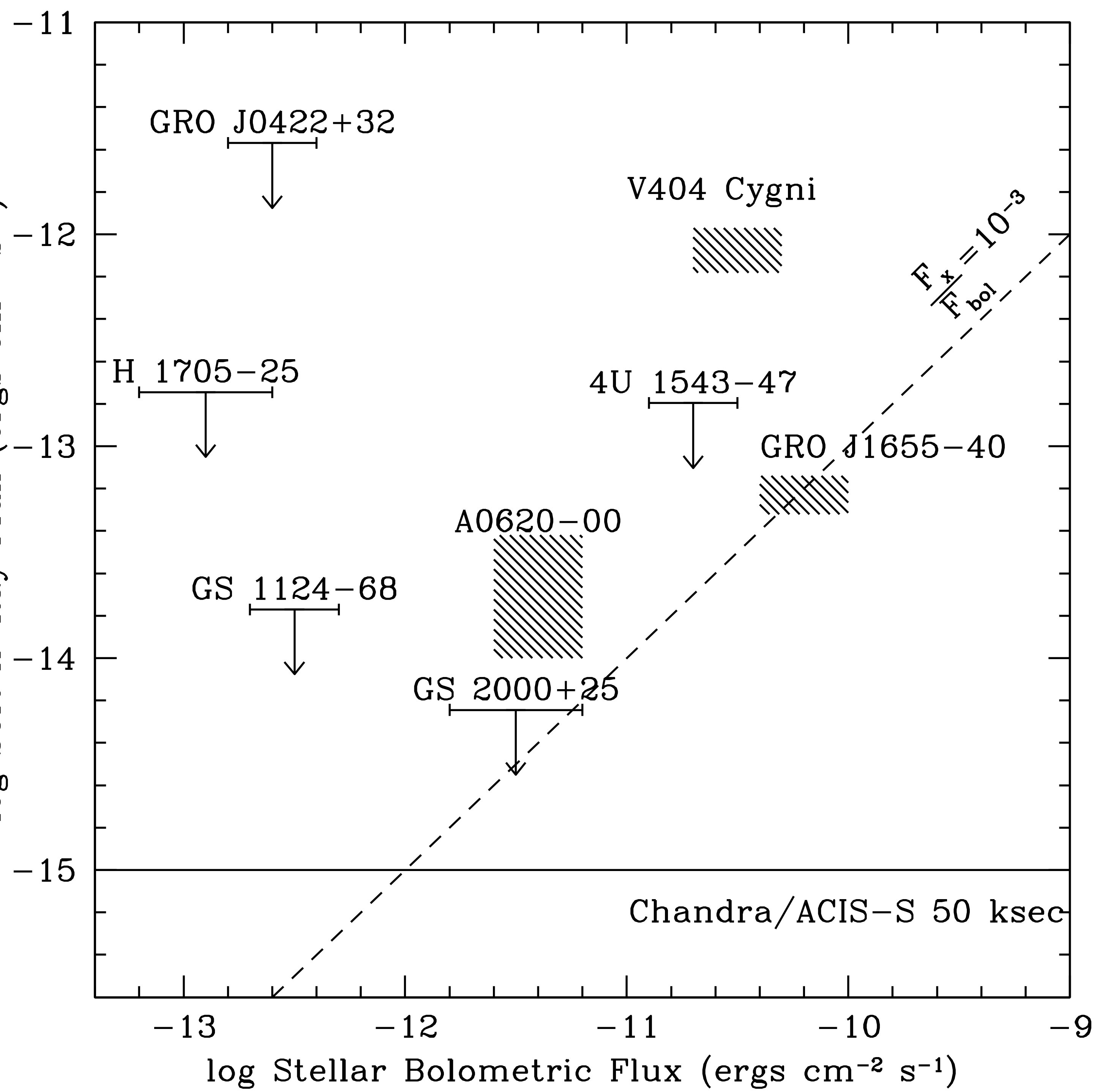
[c]Measurements from the same data

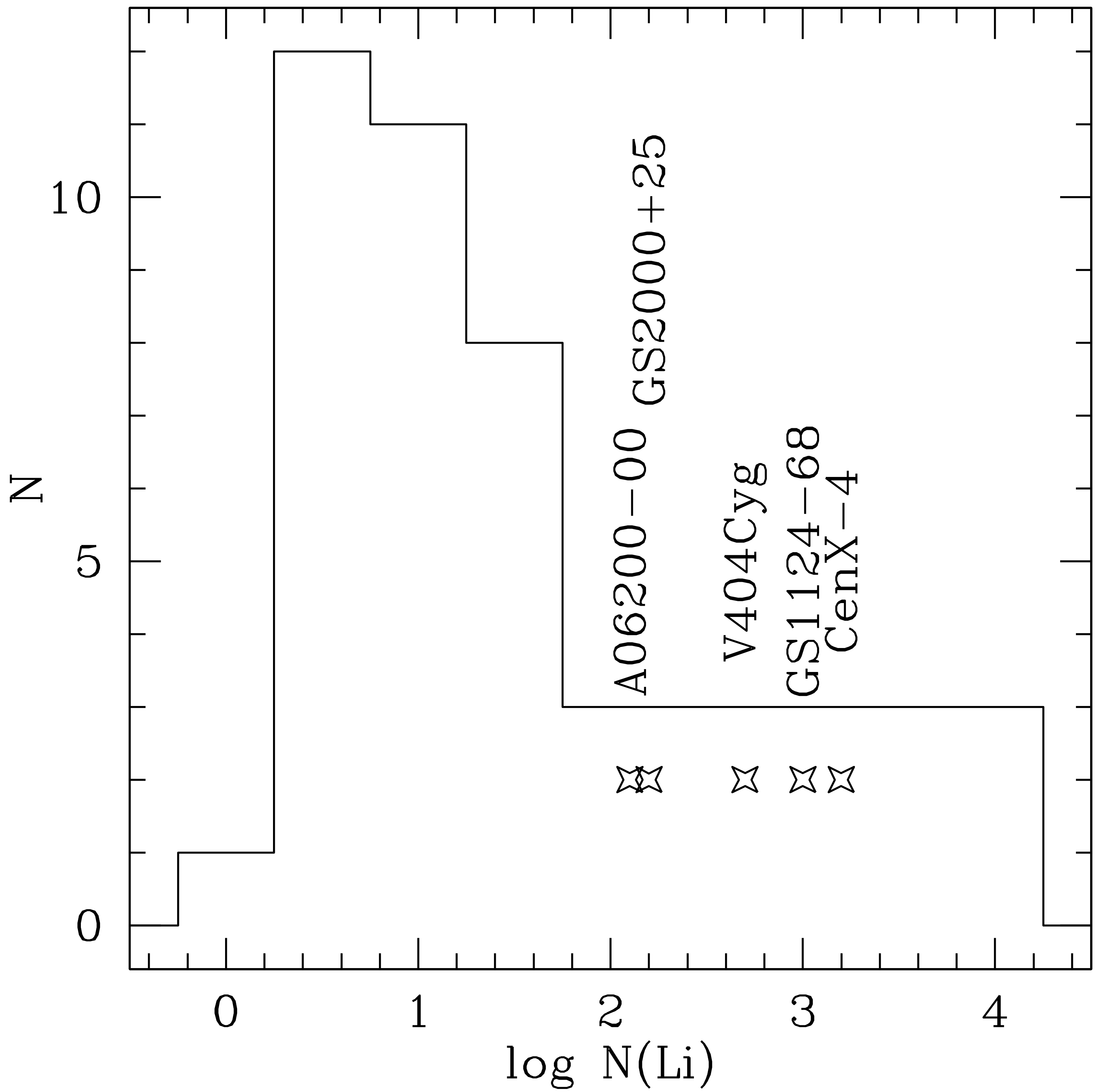
FIG. 1.— Flux ratio $L_x/L_{\rm bol}$ vs. binary orbital period for RS CVns (small points; Dempsey et al.1993b), BHCs (filled points), NSs (open points) and a best-fit relation found for rapidly rotating, late-type isolated dwarfs (where we use their rotation period; Singh et al. 1999). Of the three detected BHCs, A0620−00 and GRO J1655−40 have $L_x/L_{\rm bol}$ consistent with coronal emission ($L_x/L_{\rm bol} \lesssim 10^{-3}$), while V404 Cyg is at least an order of magnitude above this. The four detected NSs are 1-3 orders of magnitude above this limit as well.

FIG. 2.— X-ray flux vs. stellar bolometric flux for X-ray detected BHCs (shaded regions) and 2σ upper-limits. The broken line is $F_x/F_{\rm bol}$=10^{-3}. The bottom line is the *Chandra*/ACIS-S 50ksec detection limits for a $N_{\rm H,22}$=0.2, kT_{RS}=1.0 keV source (assuming 10 counts for a detection). Detection of X-rays from GRO J0422+32, GS 1124-68, and H 1705−25 with *Chandra* would be well above the level expected from coronal emission. GS 2000+25 is close to the $L_x/L_{\rm bol}$=10^{-3} limit and may be detected. While 4U 1543−47 is apparently well within X-ray detectable range, we expect none will be detected (see text).

FIG. 3.— Distribution of detected lithium abundances in chromospherically active systems, and the detected values for five SXTs. The bin width is 0.5 dex in N(Li). The SXT abundances have uncertainties of $\sim$0.5 in dex. While the SXTs have, on average, higher Li abundances by $\times$10, these are not such that Li production mechanisms involving a compact object are required, as they are well within the range observed from from RS CVns, which do not have compact objects.


SXTs and Coronal X-ray Sources
GRO J0422+32
4U1608-522
AqlX-1
4U 1705-25
CenX-4
GS 1124-68
4U2129+47
V404Cyg
4U 1543-47
A0620-00
GS 2000+25
GROJ1655-40
(RS CVns)
(Isolated Dwarfs)
P_orb (days)
10^2
10^1
1
0.1
10^-2
10^-3
10^-4
10^-5
10^-6
0.1
1
10


GRO J0422+32
V404 Cygni
H 1705−25
4U 1543−47
GRO J1655−40
A0620−00
GS 1124−68
GS 2000+25
Chandra/ACIS−S 50 ksec
$\frac{F_x}{F_{bol}} = 10^{-3}$
−11
−12
−13
−14
−15
−13
−12
−11
−10
−9
log Stellar Bolometric Flux (ergs cm^{-2} s^{-1})



N
10
5
0
0
1
2
3
4
log N(Li)
GS2000+25
A0620−00
V404Cyg
GS1124−68
CenX−4